TRULOB: Tree Register Updating for Loblolly Pine

(An Individual Tree Growth and Yield Model for Managed Loblolly Pine Plantations)

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Abstract. A tree-level growth and yield model for managed loblolly pine plantations was developed using data from permanent remeasurement plots throughout much of the natural range of the species. The model was constructed around individual tree growth and prediction equations which reflect diameter, survival and height-diameter development. Appropriate modifications have been made to the equations to reflect response to management treatments including thinning, midrotation fertilization and hardwood control. Test results indicate the model should provide reliable estimates of tree growth, diameter distribution and stand yields for many stand conditions and management regimes.

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INTRODUCTION

Loblolly pine (Pinus taeda L.) is one of the most productive tree species in the southern United States. Wood produced from loblolly pine plantations is processed for pulp and paper products as well as sawn, peeled and chipped for construction material. Increasingly, plantations of loblolly pine are being intensively managed by applying silvicultural treatments to enhance their productivity. Important silvicultural tools available to managers include midrotation thinning, fertilization and hardwood control. Thinning provides an opportunity to obtain intermediate cash flows from wood harvested in thinning operations, improve the quality of the residual stand by removing slow-growing and damaged or diseased trees and shift future growth of the stand to the larger, better quality residual trees. Fertilization and hardwood control stimulate loblolly pine growth and development by enhancing nutrient availability and reducing competitive pressure from surrounding hardwoods. Therefore, there is a need for growth and yield models which can reliably forecast future yields for managed plantations that have received these treatments. Such models should be useful to foresters, silviculturalists, researchers and others charged with managing loblolly pine plantations.

The objective of this work was to produce a growth and yield model which could be used for a variety of purposes including inventory updating, harvest scheduling, predicting wood yields for different stand conditions and evaluating the effects of silvicultural practices on stand dynamics and wood production. In order to accomplish this objective, two criteria were established to guide the model development process. The first was that predictive ability of the model would be of primary concern. That is, both individual component equations and the model as a whole should predict well at both the individual tree and stand level. The second criterion was that component equations and the overall model should reflect our understanding of how loblolly pine trees grow and develop through time. Including such biological and physical precepts in the model development process increases the likelihood that the model will perform well for stand conditions outside the range of the data used in its development. This makes the model more reliable when applied to other data and when extrapolated to conditions beyond those reflected in the development data. It also provides a more robust framework for any future enhancements such as the inclusion of other silvicultural treatments.

The following sections summarize data sources, modeling rationale and model performance for TRULOB, a tree-level growth and yield model for managed loblolly pine plantations.

DATA

Thinned and unthinned regionwide

Tree data were available from loblolly pine plantations established on cutover sites from much of the natural range of the species. One hundred eighty-six plot locations were established during the 1980-1982 dormant seasons in 8- to 25-year-old (mean=15) plantations in the southern Coastal Plain and Piedmont. Site and stand conditions at plot establishment for these locations were summarized by Burkhart et al. (1985). At each location, three plots, comparable in initial site index, number of trees and basal area per acre, were established: (1) an unthinned control plot, (2) a lightly thinned plot from which approximately one-third of the basal area was removed, and (3) a heavily thinned plot from which approximately one-half of the basal area was removed. Thinnings were primarily from below removing smaller, poorly formed and slower growing trees. However, the considerations of spacing and stem quality dictated the removal, in some cases, of selected larger trees.

Five measurements, one taken at plot establishment and four subsequent remeasurements, have been completed with a measurement interval of three years. While some plots have been abandoned during this period due to heavy insect attacks, hurricane damage, or other problems, observations over the twelve-year period were obtained for most of the plots. One site index value was determined for each plot using the measurement closest to index age (25 years). Dominant height was defined as the average height of the dominant and codominant trees. The site index equation from Burkhart et al. (1987), which was developed from these data, was used to compute site index. Site index ranged from 40 to 85 feet (mean = 60; std. dev. = 8.5). Table 1 summarizes other pertinent stand conditions for these plots at establishment and twelve years later.

Table 1. Means and standard deviations (in parentheses) of plot characteristics for unthinned, light-thin and heavy-thin Coastal Plain and Piedmont plots at establishment and at the fourth remeasurement.

	Unthinned		Light-thin		Heavy-thin	
Variable	Establishment	12 years	Establishment	12 years	Establishment	12-years
Age (years)	15 (4)	27 (4)	15 (4)	27 (4)	15 (4)	27 (4)
Trees/ac.	567 (137)	440 (105)	338 (77)	311 (69)	257 (63)	241 (59)
Basal area/ac	110 (35)	151 (28)	77 (25)	127 (23)	63 (21)	113 (23)
Percent basal area left	---	---	0.73 (0.07)	---	0.59 (0.08)	---

Data from 767 stem analysis trees were available for developing tree volume equations suitable for use in TRULOB. Some of the data (437 trees from previously unthinned plantations) were collected from the thinning study plots at establishment (Amateis and Burkhart 1987). The balance (330 trees) was obtained from the same plots at the fourth remeasurement during a second thinning, twelve years after plot establishment and first thinning.

During the second thinning, two trees were randomly selected from trees on the plots and marked for removal. Then additional trees making the balance of the number of trees prescribed for removal were marked. For lightly and heavily thinned plots, actual trees selected by the random process were cut down for analysis. In the control plots, however, trees to be removed were first randomly selected and then trees characteristically similar (dbh, total height, stem form) to those randomly selected were felled from trees in the buffer zone bordering the plots. The selected trees were sectioned at 4-ft intervals from stump to a top diameter of approximately two inches. Volume of each section was calculated and accumulated to obtain total inside and outside bark volume as well as volume to various heights. Table 2 presents summary statistics for the stem analysis data.

Table 2. Summary statistics for 767 stem analysis trees used for developing tree volume equations for TRULOB.

Variable	Mean	Minimum	Maximum
Dbh (in.)	7.2	2.4	13.9
Total height (ft.)	49.5	12.9	85.0
Total volume (ft^3 ib)	6.05	0.25	26.19
Total volume (ft^3 ob)	7.51	0.36	31.87

Fertilized and unfertilized regionwide

Tree data were available from fertilized and unfertilized permanent remeasurement plots from the North Carolina State Forest Nutrition Cooperative’s (NCSFNC) Regionwide 13 Study. Plots were established in existing midrotation plantations during 1984-1985 at 13 sites located across the southeastern United States (Table 3).

Table 3. Summary statistics of plot characteristics at establishment for 13 installations of the NCSFNC Regionwide 13 study.

	Mean	St. Dev.	Min.	Max.
Stand age (years)	12.8	1.2	11	14
Site index (ft)	61.3	5.9	53	74
Trees/ac	516	165	205	939
Basal area (sq ft/ac)	87.9	17.1	46.3	134.2
Dq (in)	5.72	0.65	4.14	7.70
Hd (ft)	37.5	5.1	25.2	48.8

At each study location, four levels of nitrogen (0, 100, 200, 300 lbs N/ac) and three levels of phosphorus (0, 25, 50 lbs P/ac) were applied using a factorial experimental design. At each location, two or four replicates of the basic twelve treatment matrix were established. Rigorous guidelines for selection of candidate stands and blocking of plots were used to minimize within site variation for stand characteristics and soil type. Plots within a block generally did not vary more than 3 feet in dominant height, 10 sq. ft/ac in stand basal area and 80 stems/ac at study establishment. The observed rates of mortality during the eight-year study period were 5.8 percent of the total stem number in unfertilized plots, 6.1 percent in the plots fertilized with 100 lbs N/ac, 7.1 percent in the plots fertilized with 200 lbs N/ac and 8.6 percent in the plots fertilized with 300 lbs N/ac.

Measurement plots included a minimum of 30 to 40 trees surrounded by a treated buffer zone of at least 30 feet. Diameter at breast height and total height were measured on all trees in each plot. Measurements were carried out at 2-year intervals during the dormant season. Data included 17,900 trees from 276 sample plots. Total number of growth observations was 57,900.

Unthinned Coastal Plain

Stand data were available from loblolly pine plantations established on cutover sites in the Coastal Plain areas of Alabama, Florida, Georgia, North Carolina and South Carolina. Seven hundred twenty nine permanent remeasurement plots were established in these plantations at age two and remeasurements occurred at three-year intervals to age 14, 17 or, in some cases, to age 20.

Site preparation methods prior to plantation establishment consisted primarily of chop, burn, disk, bed, KG or some combination of these treatments. A general soil drainage class (poor, moderately well or excessive) was known for each site. Site index values averaged 65 feet (std. dev. = 13.0 feet). Table 4 presents average survival and basal area values for selected ages in the data set.

Table 4. Mean survival and basal area for unthinned Coastal Plain data at ages 2, 8 and 14 (standard deviations in parentheses).

Variable	Age		
	2 (n=831)	8 (n=722)	14 (n=116)
Number surviving per acre	548 (310)	472 (277)	378 (252)
Basal area (sq. ft./ac.)	9.2 (11.4)	37.3 (25.7)	98.0 (46.6)

MODEL DEVELOPMENT

The basic procedure followed for developing the component models used in TRULOB was to use data from plot establishment and the first three remeasurements for model development and data from the fourth remeasurement for testing. Final models were reparameterized using all available data. For the fertilizer response models, the NCSFNC Regionwide 13 data were randomly divided into two parts of equal sizes. Models were fitted and tested using double cross-validation procedures. Again, final models were fitted using all available data.

Generally, model selection was based on (1) predictive ability, (2) biological rationale, (3) logical relationships, (4) compatibility with other selected models, and (5) simplicity and efficiency. The following sections provide a brief summary of the major component equations developed for TRULOB.

Stand-level survival for young stands

The model developed by Pienaar and Shiver (1981):

$$\ln N_2 = \ln N_1 + b_1 [A_2^{b_2} - A_1^{b_2}] \tag{1}$$

where A_1, A_2 = stand age (years) at time 1 and 2, respectively
N_1, N_2 = number of trees per acre at A_1, A_2, respectively
b_1, b_2 = parameters to be estimated

was chosen for modeling survival in young stands prior to crown closure. This model assumes that the relative mortality is density-independent and not affected by site index. During preliminary analyses using the young stand data there appeared to be differences in survival between stands established on poorly drained sites where there was no bedding prior to planting and the other drainage/site preparation areas.

In order to determine if separate b_1 and/or b_2 coefficients were needed for the poor drainage/no bedding regime, a full versus reduced model F-test was performed. Results showed that the b_1 coefficient was significantly different between the poor drainage/no bedding regime and all the other drainage/site preparation regimes. The b_2 coefficient, however, was not significantly different. Thus, the pre-competitive stand model was defined as:

$$\ln N_2 = \ln N_1 - [0.000997 + 0.000724\, D]\, [A_2^{2.0525} - A_1^{2.0525}] \tag{2}$$

$$MSE = 0.0058$$

where

D = 1 if site is poorly drained and not bedded; 0 otherwise

and all other variables are as previously defined. All parameter estimates were significant at the 0.05 level.

In order to evaluate the suitability of Equation (2), a percent residual number of trees per acre surviving ((obs-pred)/obs*100) was computed for each observation. The mean percent residual number of trees per acre for the poor drainage/no bedding regime at age 5 was -0.6 (std. dev. = 6.9) and at age 8 was -1.0 (std. dev. = 19). For the other regimes, the mean percent residual at age 5 was 0.2 (std. dev. = 4.0) and at age 8 was -0.4 (std. dev. = 7.9). The data were grouped into eight classes for each drainage/site preparation regime according to surviving trees per acre (<150, 150-300, 300-400, 400-500, 500-650, 650-800, 800-900, >900). Table 5 shows the mean percent residuals for these survival classes.

Table 5. Mean percent residual ((obs-pred)/obs*100) for 1402 survival observations by density class for two drainage/site preparation regimes using Equation (2).

	Poor drainage/no bedding			All other drainage/site preparation		
Density	Mean	Std Dev	N	Mean	Std Dev	N
<150	-15.6	19.3	23	-2.1	9.3	55
150-300	-0.5	18.5	128	-0.1	6.0	328
300-400	-2.1	10.5	24	-4.5	11.2	43
400-500	-0.6	16.1	65	1.5	2.6	168
500-600	-4.5	10.3	21	-7.7	13.9	32
600-700	0.2	8.7	45	-0.2	5.0	104
700-800	1.7	5.6	43	1.1	3.9	95
>800	2.7	4.7	73	1.0	3.0	155

Dominant height / site index

An appropriate dominant height/site index equation is a central component equation of most growth and yield models. This is because many stand dynamic relationships are influenced by site quality. As a base model, we selected the site index equation developed by Amateis and Burkhart (1985) and formulated it in its untransformed configuration (Cao, 1993):

$$H_2 = e^{\ln H_1 (A_1/A_2)^{b_1} e^{b_2\left(A_2^{-1} - A_1^{-1}\right)}} \qquad (3)$$

where: A_1, A_2 = age (years)

H_1, H_2 = average height of dominant and codominant trees (ft.) at A_1 and A_2

b_1, b_2 = parameters to be estimated.

Using the thinned and unthinned region-wide data, we examined dominant height growth relationships after thinning for the three treatments. Over the first few years after treatment, the thinned plots produced less height growth than the unthinned plots. This differential reached a maximum before the second remeasurement (6 years after thinning) and gradually declined thereafter. By 12 years after thinning the unthinned and light-thinned plots have converged with the heavy-thin plots growing slightly more on the average. This height growth suppression following thinning has also been documented by other researchers (Ginn et al., 1991; Harrington and Reukema, 1983). In order to examine this effect more closely, Equation (3) was fitted using the dominant height data from thinned and unthinned plots. Then, Equation (3) was modified by incorporating a thinning response function in such a way that the path-invariant property of the function was maintained (Smith, 1994):

$$H_2 = e^{\ln H_1 (A_1/A_2)^{b_1} e^{b_2\left(T_2 A_2^{-1} - T_1 A_1^{-1}\right)}} \qquad (4)$$

and

$$T = \left(\frac{BA_a}{BA_b}\right)^{\frac{r(-(A-A_t)^2 + k(A-A_t))}{A^2}}$$

A_t = stand age at thinning (years)

BA_a = stand basal area after thinning (ft^2)

BA_b = stand basal area before thinning (ft^2)

r, k = parameters

Equation (4) was also fitted using the thinned and unthinned plot data. Table (6) presents the fit statistics for each model.

Table 6. Mean squared error, parameter estimates and asymptotic standard errors (in parentheses) for Equations (3) and (4) fitted to the thinned and unthinned plot data.

Parameter	Equation (3)	Equation (4)
b_1	-0.0775 (0.0051)	-0.0525 (0.0055)
b_2	-1.9160 (0.0937)	-2.4007 (0.1039)
r	---	-0.7384 (0.1610)
k	---	12.878 (2.7719)
	MSE = 3.19	MSE = 3.00

Inclusion of the thinning response function in the dominant height growth equation reduced the error sum of squares by about six percent and produced a model more responsive to the effects of thinning on dominant height growth. Thus, Equation (4) was selected as the dominant height growth model for TRULOB. By substituting a site index value, S, for H_1 at $A_1 = A_I$ and solving for S, Equation (5) can be used to estimate site index from dominant height:

$$S = e^{\left(\frac{\ln(H_1)}{(A_I/A_1)^{b_1} e^{b_2\left(T_1 A_1^{-1} - T_I A_I^{-1}\right)}}\right)} \qquad (5)$$

Existing stand initiation

When an existing tree list is not available, TRULOB generates one using the Weibull distribution. If stand age is less than eight, Equation (2) is used to advance stand survival through the juvenile stage to age eight which is approximately the time of crown closure and the onset of intraspecific competition. When stand age is greater than seven, total basal area is predicted from the equation

$$\ln(BA) = b_1 + \frac{b_2}{A} + b_3 \ln(Hd) + b_4 \ln(N) + b_5 \ln(S) \tag{6}$$

when the percent hardwood basal area is not specified, and

$$\ln(BA) = b_1 + \frac{b_2}{A} + b_3 \ln(Hd) + b_4 \ln(N) + b_5 \ln(S) + b_6 PHDWD \tag{7}$$

where PHDWD = percent of total basal area in hardwoods and all other variables as previously defined, when the percent hardwood basal area is specified. Equation (8), fitted to the region wide unthinned plots, is then used to calculate average stand diameter and the Weibull parameters are recovered:

$$\ln(DQ - DA) = b_1 + \frac{b_2}{A} + b_3 \ln(N) \tag{8}$$

where DQ = quadratic mean dbh (in)
DA = arithmetic mean dbh (in)
and all other variables are as previously defined.

Two equations for predicting the location parameter (related to minimum dbh) of the three parameter Weibull distribution were specified and fitted to the unthinned region wide data. When percent hardwood basal area is not specified,

$$APARM = b_1 + b_2 Hd + b_3 N \tag{9}$$

is used in TRULOB to predict the location parameter. When percent hardwood basal area is specified,

$$APARM = b_1 + b_2 Hd + b_3 N + b_4 PHDWD \tag{10}$$

where APARM is the location parameter of the Weibull distribution and all other variables are as previously defined. Table 7 contains the parameter estimates and fit statistics for Equations (6)-(10).

Table 7. Mean squared error, parameter estimates and asymptotic standard errors (in parentheses) for Equations (6)-(10) fitted to the unthinned region wide data.

Parameter	Equation (6)	Equation (7)	Equation (8)	Equation (9)	Equation (10)
b_1	-3.10633 (0.26822)	-2.43453 (0.26054)	-0.61472 (0.34104)	0.78620 (0.2364)	1.06707 (0.24335)
b_2	-6.22094 (1.52141)	-6.85252 (1.42647)	-9.13668 (0.93560)	0.07173 (0.00282)	0.07013 (0.00282)
b_3	0.54576 (0.02192)	0.49701 (0.021135)	-0.10757 (0.05648)	(-0.00201) (0.00025)	-0.00221 (0.00025)
b_4	0.67810 (0.12020)	0.61450 (0.11277)	---	---	-2.1593 (0.52355)
b_5	0.54738 (0.12085)	0.53524 (0.11320)	---	---	---
b_6	---	-0.85662 (0.08807)	---	---	---
MSE	0.0183	0.016	0.145	0.596	0.583

The Weibull recovery routine divides the diameter distribution into tenth-inch classes creating a tree list of diameters and frequencies. From this point forward the stand is projected and yield predictions made using the individual tree component equations described in the following sections.

Crown ratio prediction

Crown ratio is an appropriate index for tree growth because it is very sensitive to changes in stand density and tree vigor. Therefore, an accurate crown ratio prediction model is a central component equation of many individual tree growth models. Liu et al. (1995) found that thinning significantly influences crown development, and proposed a crown ratio prediction model based on the biological crown response to thinning. Subsequent analysis showed that to include the ratio of tree height to dominant height in the crown ratio prediction model would improve its predictive ability. Such a ratio reflects the amount of solar radiation a tree would receive relative to its neighbors. Thus a new model with the form:

$$Cr = \left(1 - T * \exp\left(\left(b_1 + \frac{b_2}{A}\right)\frac{D}{H} + b_3\frac{H}{HD}\right)\right)^{b_4} \qquad (11)$$

where: Cr = crown ratio
A = age (years)
HD = average dominant and codominant height (ft.)
H = tree total height (ft.)
D = diameter at breast height (in.)
b_1,- b_4 = parameters.

was developed and fitted to the thinned and unthinned data. The parameter estimates and standard errors (in parentheses) are $b_1 = -0.4673$ (0.0224), $b_2 = -49.713$ (0.1360), $b_3 = -0.5177$ (0.0046), $b_4 = 1.9718$ (0.01388), $r = 0.0703$ (0.0312), $k = 175.30$ (63.339), MSE = 0.00521.

Individual tree diameter increment

One common approach to modeling diameter growth is to use the potential diameter increment (diameter increment of an open-grown tree) as a base, or maximum, and then modify it to reflect stand conditions. This general approach was followed and the following equation was specified:

$$DIN = PDIN\left(b_1 Cr^{b_2} \exp\left(b_3\left(1 - \frac{\bar{D}}{D}\right) + b_4\left(1 - \frac{BA_b}{BA_a}\right)\right)\right) \qquad (12)$$

where $\bar{D}$ = $(BA / N / 0.005454)^{0.5}$ (quadratic mean dbh, inches)

PDIN = potential diameter increment from open-grown trees (Daniels and Burkhart, 1975) (in.)
DIN = diameter increment (in.)
b_1-b_5 = parameters to be estimated and all other variables are as previously defined.

Using data from the first three remeasurements, Equation (12) was fitted to the combined thinned and unthinned plot data. The residuals exhibited no obvious trends by thinning treatment, age, site, stand density or tree characteristics.

A similar model was specified to account for the amount of hardwood competition in the stand:

$$DIN_{hw} = PDIN\left(b_1 Cr^{b_2} \exp\left(b_3\left(1 - \frac{\bar{D}_{hw}}{D}\right) + b_4\left(1 - \frac{BA_a}{BA_b}\right)\right)\right) \qquad (13)$$

where $\bar{D}_{hw}$ = $((BA + BA_{hw}) / N / 0.005454)^{0.5}$

BA = basal area (ft^2/ac)
BA_{hw} = hardwood basal area (ft^2/ac)

and all other variables as previously defined.

Parameters in Equations (12) and (13) can be estimated using nonlinear least squares techniques and will give suitably precise estimates of individual tree diameter growth. However, estimates of diameter class and stand-level predictions may be inaccurate because of the cumulative error resulting from individual tree predictions, especially when projections over long time periods are made. We can ensure that individual tree diameter growth models not only provide precise individual tree predictions but also give precise diameter class and stand-level estimation by constraining the diameter increment of trees in the same diameter class to be consistent with diameter class and stand-level values (Zhang et al., For. Sci., in press). Therefore, the parameters in Equation (12) were estimated in the following system of equations:

$$\begin{cases} DIN_{ji,t} = PDIN_t b_1 Cr_{ji,t}^{b_2} \exp\left(b3\left(1 - \frac{\overline{D}_t}{D_{ji,t}}\right) + b_4\left(1 - \frac{BA_a}{BA_b}\right)\right) \\ G_{j,t+1} = 0.005454 \sum_{i=1}^{n_{j,t+1}} \left(D_{ji,t} + PDIN_t b_1 Cr_{ji,t}^{b_2} \exp\left(b3\left(1 - \frac{\overline{D}_t}{D_{ji,t}}\right) + b_4\left(1 - \frac{BA_a}{BA_b}\right)\right)\right)^2 \end{cases} \tag{14}$$

where $DIN_{ji,t}$ = diameter increment (in.) of the ith tree in the jth diameter class at age t
$G_{j,t+1}$ = basal area (sq. ft/ac) of the jth diameter class
$PDIN_t$ = potential individual tree diameter increment (in.) At age t
$Cr_{ji,t}$ = crown ratio of the ith tree in the jth diameter class at age t
$D_{ji,t}$ = diameter (in.) of the ith tree in the jth diameter class at age t
and all other variables are as previously defined.

Equation System (14) was fitted to the data with a SAS/IML algorithm developed for estimating multiresponse regression based on the theory developed by Bates and Watts (1987, 1988). A similar system of equations was estimated for DIN_{hw} (Table 8).

Table 8. Parameter estimates and standard errors (in parentheses) for Equation System (14) applied to dbh increment data with and without hardwood component.

Parameter	Equation System (14) without hardwoods	Equation System (14) with hardwoods
b_1	0.49466 (0.000735)	0.49672 (0.000765)
b_2	1.0348 (0.00174)	1.0232 (0.00176)
b_3	0.87978 (0.00253)	0.84759 (0.00250)
b_4	0.80428 (0.00268)	0.79775 (0.00269)
MSE (for DIN)	0.00881	0.00887

Tree survival prediction model

Individual tree models predict the probability of survival for each tree involved in the growth projection (Clutter et al. 1983). Conceptually, the individual survival probability should be between [0, 1] for any growth interval. Of the functions with this property, logistic regression has been one of the most widely employed (Hamilton 1974; Lowell and Mitchell, 1987; Hamilton 1990; Vanclay, 1991; Avila and Burkhart 1992). Avila and Burkhart (1992) proposed a model based on the logistic function which is appropriate for describing individual tree survival probability for loblolly pine trees:

$$PLIVE = \frac{1}{1 + \exp\left(-\left(b_1 + b_2 Cr + b_3 H/HD + b_4 \bar{D}/D\right)\right)} \tag{15}$$

where PLIVE = 0 for a dead tree; 1 for a living tree
b_1-b_4 = parameters

and all other variables are as previously defined. If hardwood competition is taken into consideration, D_{hw} can be used instead of ,, in Equation (15).

Since mortality is a complex phenomenon, it is difficult to predict precisely either the regular mortality (normal suppression induced) or the combination of regular and irregular mortality. Preliminary projection results using Equation (15) for unthinned plots showed it underestimated greatly the number of dead trees. This implies that some additional information needs to be incorporated into the model to improve its predictive ability. It should be possible to improve the predictive ability of individual tree survival models if mortality information on a stand or diameter class level can be used in developing the model. Therefore, another approach to estimating parameters of the survival model was used and can be described as follows. Suppose there are $n_{i,t}$ trees in the ith diameter class at age t. After one year, some of the $n_{i,t}$ trees die, some of them stay in the ith diameter class, and others grow into larger diameter classes. If $n_{i,t+1}$ is used to denote the number of live trees after one year of these original $n_{i,t}$ trees, then we have:

$$n_{i,t+1} = \sum_{j=1}^{n_{i,t}} PLIVE_{ijt} \tag{16}$$

where $PLIVE_{ijt}$ = the survival probability of the jth tree in diameter class I at age t.

Combining Equations (15) and (16), we obtain the following seemingly unrelated regresssion (SUR) equation system:

$$\begin{cases} \hat{PLIVE}_{jt} = \dfrac{1}{1 + \exp\left(-\left(b_1 + b_2 Cr + b_3 \dfrac{H}{HD} + b_4 \dfrac{\bar{D}}{D}\right)\right)} \\ \hat{n}_{i,t+1} = \displaystyle\sum_{j=1}^{n_{i,t}} \hat{PLIVE}_{ijt} \end{cases} \tag{17}$$

The SAS PROC SYSNLIN (SAS, 1990) was used to estimate the parameters of Equation System (17) (Table 9).

Table 9. Parameter estimates and fit statistics (standard errors in parentheses) for Equation System (17) for predicting thinned and unthinned individual tree survival including and not including hardwood basal area in the computation of quadratic mean dbh.

Parameter	Equation System (17) (unthinned not including hdwd)	Equation System (17) (unthinned including hdwd)	Equation System (17) (thinned not including hdwd)	Equation System (17) (thinned including hdwd)
b_1	-4.7819(0.0861)	-4.8038(0.0864)	-1.1447(0.1221)	-1.1995(0.1219)
b_2	9.0717(0.1082)	9.0680(0.1081)	7.8177(0.1449)	7.8409(0.1453)
b_3	6.2759(0.0848)	6.2971(0.0850)	3.6261(0.1313)	3.6627(0.1315)
b_4	0.0983(0.0162)	-0.0999(0.0158)	-0.0439(0.0207)	-0.0317(0.0201)
MSE (PLIVE)	0.1020	0.1020	0.0610	0.0610

Tests using Equation System (17) showed that some predictive ability at the individual tree level is sacrificed in order to obtain more reliable estimates of survival at the diameter class and stand level.

Tree height prediction model

In the past decade, considerable research has focused on studying stand and tree response to thinning. From this research it is clear that thinning has a positive influence on diameter increment. However, the influence of thinning on total tree height has been rarely reported. It is generally thought that height growth is mostly independent of stand density except in stands with extremely high or low density. Whether thinning has obvious effects on height growth or not, it should be reasonable to expect that the relationship between total height and dbh, which is a key relationship affecting tree volume, will be different in thinned and unthinned stands. Therefore, an examination of the influence of thinning on tree height-diameter relationships was conducted before selecting a height prediction model. As a result, a new model for height prediction was developed:

$$H = b_1 \, HD^{\,b_2} \, 10^{\left(\frac{b_3}{A} + \left(\frac{1}{D} - \frac{1}{D_{max}} \right) \left(b_4 + b_5 \frac{\log_{10} N}{A} \right) \right)} \qquad (18)$$

where H = total tree height (ft)
HD = average height of the dominant and codominant trees (ft)
N = number of trees per acre
D_{max} = maximum diameter of the stand (in.)
b_1-b_5 = parameters
and all other variables are as previously defined.

Total height observations from the first three remeasurements were used to estimate the parameters in Equation (18). The estimated parameters (with standard errors in parentheses)are: b_1 = 1.4504 (0.00965), b_2 =

0.93664 (0.00141), b_3 = -0.44126 (0.012685), b_4 = -1.35037 (0.007875), and b_5 = 2.8095 (0.05485). MSE for Equation (18) is 9.94 feet.

Tree volume equations

Tree volume equations are required in TRULOB for determining the wood content of standing trees to any merchantable limit. The combined variable equation (Equation (19)) was fitted to the total outside bark (ob) and inside bark (ib) tree volume data from the three thinning treatments to determine if tree volume differed by treatment (Tasissa et al., 1996).

$$V_t = b_1 + b_2 D^2 H \tag{19}$$

where V_t = total ib or ob volume (ft^3)
D = diameter at breast height (in.)
H = total tree height (ft.)
b_1, b_2 = parameters to be estimated from the data

A partial F-test indicated that the slope (b_2) for the thinned plots is significantly different from that of the unthinned plots. No significant difference, however, was observed between the slopes for the two thinning intensities. Consequently, the data from the thinned plots were combined to obtain coefficient estimates for thinned stands and data from the unthinned control plots were combined with the data collected during plot establishment to estimate coefficients for unthinned stand conditions (Table 10).

For estimating merchantable volume to any particular top limit, the volume ratio equation (Van Deusen et al. 1981; Baldwin 1987)

$$V_m = V_t \exp(b_1 (d^{b_2} / D^{b_3})) \tag{20}$$

where V_m = merchantable cubic foot volume
d = top diameter limit (in.) ob.
and all other variables are as previously defined, was applied to the tree data from thinned and unthinned plots (Table 10).

Table 10. Parameter estimates and standard errors (in parentheses) for Equations (19) and (20) fitted to the tree volume data from thinned and unthinned plots.

Coefficient	Equation (19) ob	Equation (19) ib	Equation (20) ob	Equation (20) ib
---Unthinned---				
b_1	0.21949(0.046)	-0.01039(0.048)	-0.78579(0.023)	-0.91505(0.028)
b_2	0.00238(<0.001)	0.00196(<0.001)	4.92060(0.021)	4.9332(0.021)
b_3	---	---	4.55878(0.024)	4.60614(0.024)
MSE	0.455	0.482	0.150	0.105
---Thinned---				
b_1	0.25663(0.181)	-0.13431(0.144)	-1.04007(0.062)	-1.24933(0.077)
b_2	0.00239(<0.001)	0.00203(<0.001)	5.25569(0.034)	5.22906(0.035)
b_3	---	---	4.99639(0.041)	5.02295(0.043)
MSE	1.406	0.8883	0.567	0.418

For predicting volume in board feet, the following equations are used in TRULOB depending on which log rule is selected by the user

$$\begin{aligned} International\ (1/4) &= -24.3816 + 0.005816\,(D^2H)^{1.0835} \\ Scribner &= -29.7455 + 0.01888\,(D^2H)^{1.9521} \\ Doyle &= 3.2492 + 0.00003386\,(D^2H)^{1.5651} \end{aligned} \tag{21}$$

Fertilizer response functions

Response to nitrogen and phosphorus fertilization in the TRULOB system was modeled as a multiplier function for the base individual tree growth models. Information about the duration and temporal distribution of growth response in midrotation loblolly pine stands following nitrogen fertilization is documented in NCSFNC studies reported by Ballard (1982) and NCSFNC (1992). According to these studies, tree growth increases following fertilization to a maximum response during the first four years after treatment. Thereafter, response declines rather rapidly.

The three-parameter Weibull probability density function was applied in modeling the temporal distribution of the response to fertilization

$$f(t) = \frac{C}{B}\left(\frac{t-A}{B}\right)^{(C-1)} \exp\left[-\left(\frac{t-A}{B}\right)\right]^{C} \tag{22}$$

where t = time
A = location parameter
B = scaling parameter (>0)

C = shape parameter (>0).

It has been observed that tree growth in loblolly pine stands responds to fertilization without delay. Thus, the location parameter (A) was set to zero, resulting in a two-parameter Weibull p.d.f. The Weibull function has some desirable properties that make it suitable to apply in this kind of modeling. It is a flexible function that can describe a large variety of distribution forms as a result of modifying the scaling (B) and shape © parameters. Like other probability density functions, the integral of the Weibull p.d.f equals one. To get a varying magnitude of response as a result of different fertilization treatments, the Weibull p.d.f. is scaled by multiplying it with a variable expressed as a function of the dose and the nutritional elements.

Growth response varies according to the amount and the fertilizer elements applied. Growth response increases with increasing amount of added nitrogen up to 300 lbs N/acre. The response curve typically follows a decreasing exponential trend (Wells et al. 1976; Ballard 1980). Fertilization with both phosphorus and nitrogen produces, on most sites, a greater response than the effects of nitrogen or phosphorus alone. Both fertilizer dose (lbs/acre) and fertilizer elements (N, P) were included in the function by which the Weibull p.d.f was multiplied.

Magnitude of fertilization response is affected by site as well as stand and tree characteristics. According to Duzan et al. (1982) absolute growth response increases with increasing site index, while it decreases with increasing stand basal area. The effect of tree size is also obvious; absolute growth response is greatest among the largest trees in the stand. However, the relative growth response has been found to be fairly independent of tree size as documented by Hynynen (1993) for Scots pine and by Moore et al. (1994) for Douglas-fir. In TRULOB, the effects of site index, stand density and tree size on tree growth are included in the base growth model. It is assumed that they do not affect the relative growth response following fertilization.

Analyses of the NCSFNC region-wide data produced the following fertilizer response function:

$$F_d = 1 + ((a_1 + a_2 P) N^{a_3}) \frac{c}{b} \left(\frac{time}{b} \right)^{(c-1)} \exp\left[- \left(\frac{time}{b} \right)^{c} \right] \tag{23}$$

where F_d = fertilizer growth response multiplier for diameter growth
N = nitrogen dose, lb/ac
P = 1 if fertilized with phosphorus, 0 otherwise
time = time after fertilization, years
a_1-a_3,b,c = parameters to be estimated.

In modeling height growth response following fertilization, a similar strategy to that applied in developing the diameter growth model was adopted. Preliminary analyses indicated that height growth response to fertilization did not vary by relative or absolute tree size. Therefore, modeling dominant height growth response to fertilizer should be appropriate since dominant height is a predictor variable in the height prediction equation. Base, or reference, dominant height growth was modeled as a function of age, added nutrient element, dose, and time elapsed since fertilization. As in the diameter growth model, temporal distribution of growth response was modeled using the Weibull function and applied as a multiplier to the base growth model.

$$F_h = 1 + P(a_1 N) \frac{c}{b} \left(\frac{time}{b} \right)^{(c-1)} \exp\left[- \left(\frac{time}{b} \right)^{c} \right] \tag{24}$$

where F_h = fertilizer growth response multiplier for height growth, and all other variables are as previously defined. Equations (23) and (24) are used in TRULOB to reflect the effects of fertilizer treatments on diameter and height development, respectively.

MODEL RELATIONSHIPS

The models introduced above consist of a tree list updating system. Each component equation was tested using data withheld for confirmation and found to be suitable for use in the TRULOB system. Although each equation may perform well as a separate component, the entire system of equations must be evaluated for logical trends and proper relationships at the stand and diameter distribution levels. The following figures present basic stand-level relationships predicted by the TRULOB system of equations.

Unthinned

Figures 1a - 1f present some basic stand development relationships for unthinned stands in TRULOB. In general, stand developmental relationships proceed faster on higher sites planted at greater densities.

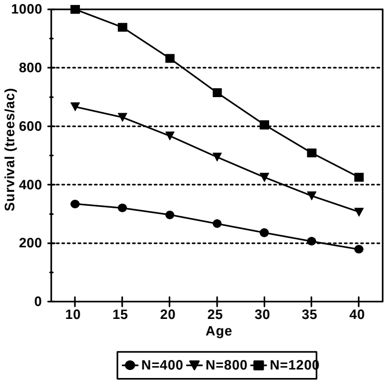

Fig. 1a. Survival trajectories for 1200, 800 and 400 trees per acre planted (site index 60).

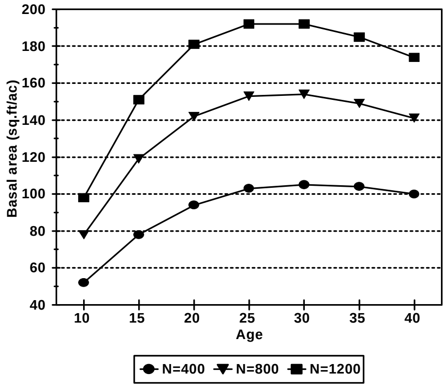

Fig.1b. Basal area trajectories for 1200, 800 And 400 trees per acre planted (site index 60).

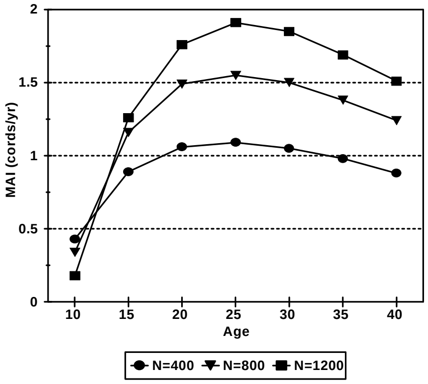

Fig. 1c. Mean annual increment for 1200, 800 and 400 trees per acre planted (site index 60).

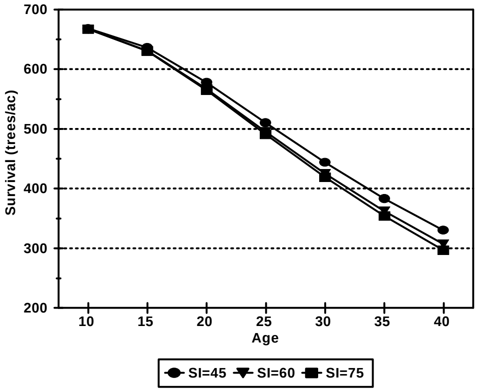

Fig. 1d. Survival trajectories for site index 45, 60 and 75 (800 trees per acre planted).

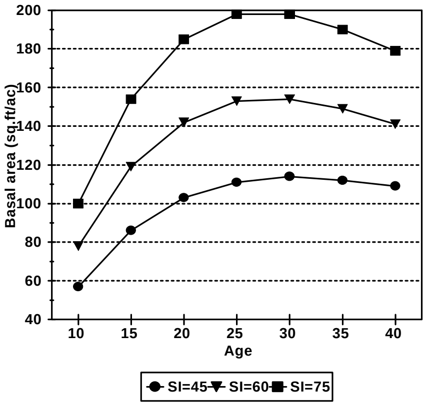

Fig. 1e. Basal area trajectories for site index 45, 60 and 75 (800 trees per acre planted).

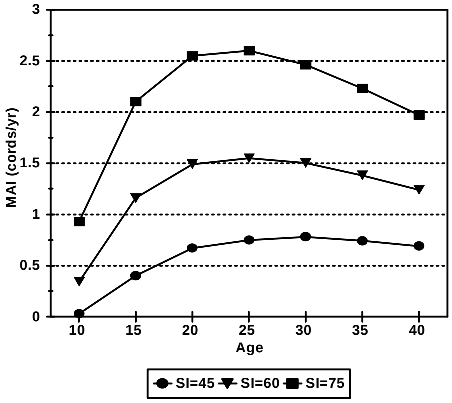

Fig. 1f. Mean annual increment (cords/yr) for site index 45, 60 and 75 (800 trees per acre planted.

Thinned-unthinned

Figures 2a-2d compare some basic stand development relationships for the average unthinned, light-thinned and heavy-thinned stand in the region-wide plantation data set. At plot establishment, the average stand conditions were age 15, site index 60, 566 trees per acre and 110 square feet per acre of basal area. Following thinning, the average light-thinned conditions were 315 trees per acre and 80 square feet per acre of basal area. For the average heavy-thinned stand, the mean residual number of trees per acre was 238 and the mean residual basal area was 65 square feet per acre. These figures present projections to age 40 which, for the average stand, is 25 years following thinning.

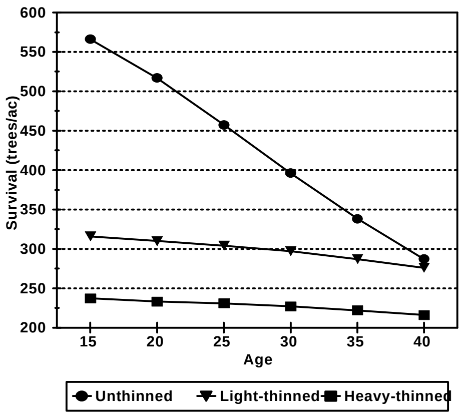

Fig. 2a. Survival trajectories (trees per acre) for the average unthinned, light-thinned and heavy-thinned stand.

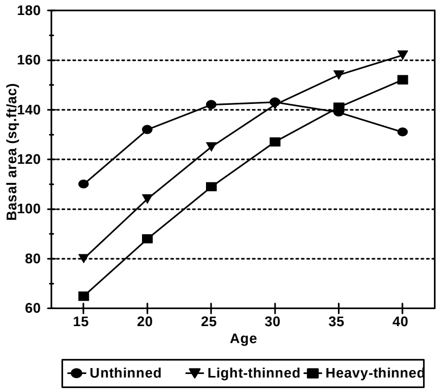

Fig. 2b. Basal area trajectories for the average unthinned, light-thinned and heavy-thinned stand.

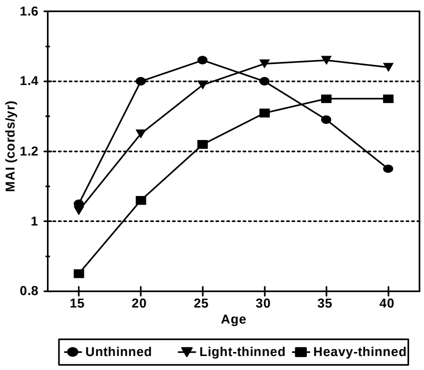

Fig. 2c. Mean annual increment (cords/year) for the average unthinned, light-thinned and heavy-thinned stand.

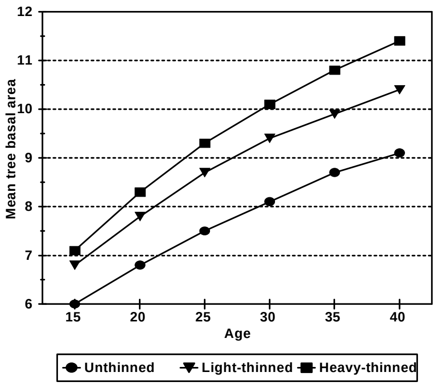

Fig. 2d. Mean tree basal area for the average unthinned, light-thinned and heavy-thinned stand.

Fertilized-unfertilized

Figures 3a-3b compare some basic stand development relationships for the average unfertilized stand with three levels of fertilization applied to the same stand: 1) no P, 200 lbs N; 2) P and 200 lbs N; 3) P and 300 lbs N. At plot establishment when fertilizer treatments were applied there were 516 trees per acre and 88 square feet of basal area with a site index of 61 feet. Stand age was 13 years.

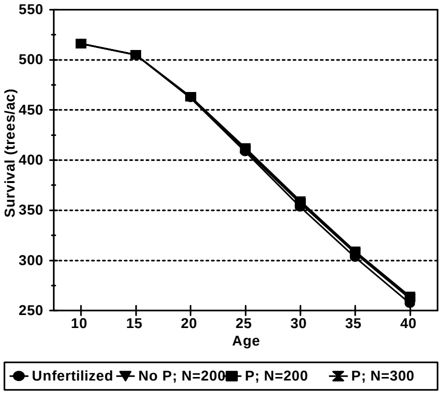

Fig. 3a. Survival trajectories for the average unfertilized stand and the same stand under three alternative fertilizer regimes.

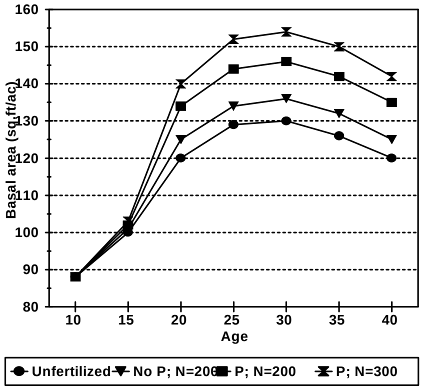

Fig. 3b. Basal area trajectories for the average unfertilized stand and the same stand under three alternative fertilizer regimes.

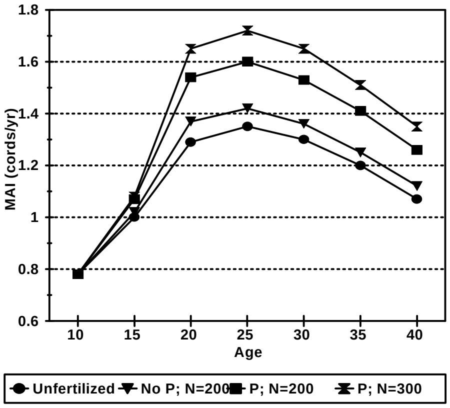

Fig. 3c. Mean annual increment for the average unfertilized stand and the same stand under three alternative fertilizer regimes.

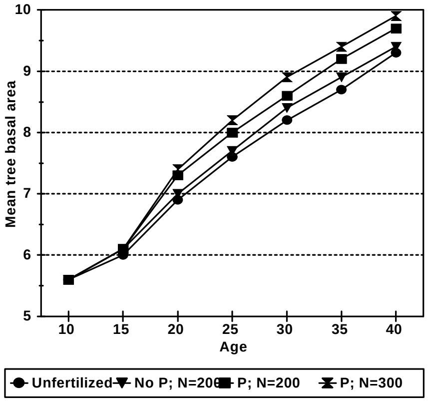

Fig. 3d. Mean tree basal area for the average unfertilized stand and the same stand under three alternative fertilizer regimes.

APPLYING TRULOB

TRULOB can be used for a variety of purposes including inventory updating, projecting a tree list for a specific stand, evaluating thinning, hardwood control and fertilization treatments and as input to management decisions. Simulation test results show that the individual tree growth models in TRULOB provide reasonably precise tree-level predictions when used separately and give acceptably precise estimation for stand-level predictions when used as an integrated model system. Consequently, the TRULOB model system should be suitable for updating tree lists for thinned, unthinned, fertilized and unfertilized loblolly pine plantation tree lists. As such it is a tool that may be useful to a variety of forestry professionals, land managers and practitioners. The following should be kept in mind by those applying the model:

- The data used to develop all component equations for TRULOB come from loblolly pine plantations growing across much of the range of the species including both the Coastal Plain and Piedmont physiographic regions. As such the model reflects the general growing conditions and yield relationships found in the data. Growth and yield relationships exhibited in TRULOB may, to a greater or lesser degree, mimic individual stands growing in specific localities.

- The data used to develop TRULOB reflect site preparation techniques common to southern plantation forestry during the late 1950s to early 1970s. On average, five percent of the total basal area of these plantations was hardwood or non-planted pine basal area. When hardwood competition levels are not explicitly specified by the user, projections from TRULOB will reflect these inherent site preparation and hardwood component characteristics.

- No plots from genetically improved plantations were used in the development of TRULOB. If projections of genetically improved stands are to be made, appropriate adjustments to the input parameters must be made by the user.

- The light-thinned and heavy-thinned plots used in TRULOB received primarily selection thinnings from below with a few plots first receiving a row thinning to provide access followed by a selection thinning. Thinnings were, for the most part, accomplished by research personnel using chain saws. Trees were selected for removal based on size, vigor, quality and spacing. All plots were thinned once and allowed to grow for twelve years. Applying TRULOB to stands thinned under different criteria, stands thinned multiple times, or making projections beyond twelve years after thinning may not be appropriate.

- The fertilizer response functions in TRULOB were developed from the NCSFNC Regionwide 13 study. These permanent plots were fertilized one time at approximately age 13 with specific amounts of P and N and allowed to grow for eight years. Applying TRULOB to stands fertilized with different nutrients at different stages of stand development or stands fertilized multiple times may not be appropriate.

- While TRULOB can be used for evaluating multiple silvicultural treatments, users should be aware that the interactions between thinning and fertilization and between fertilization and hardwood control are not reflected in the data used to develop the component growth equations. Therefore, care must be taken when projecting stands where multiple silvicultural treatments have been applied.

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TRULOB USER'S MANUAL

Preface

The following sections describe the DOS version of TRULOB, which predicts growth and yield of managed loblolly pine plantations growing on cutover site-prepared areas. The software was developed in standard FORTRAN and can be executed on any standard IBM compatible computer.

To obtain a diskette containing TRULOB write to:

Biometrics Section
Department of Forestry
Virginia Tech
Blacksburg, VA 24061-0324

or email: ralph@vt.edu

To defer the cost of development, postage and handling, a charge of $80.00 will be made. Checks should be made payable to the Department of Forestry, Virginia Tech.

Although the TRULOB software has been extensively tested and checked for accuracy and, to the best of our knowledge, contains no errors, neither Virginia Tech, the Department of Forestry, nor the authors claim any responsibility for any errors that do arise. The authors would appreciate having any errors or problems brought to their attention.

INTRODUCTION TO THE TRULOB SOFTWARE

Purpose of TRULOB

TRULOB is a computer program which can be used to predict the growth and yield of managed loblolly pine plantations growing on cutover, site-prepared areas for much of the natural range of the species. Predictions are obtained by responding to requests for stand level characteristics on a per acre basis or, alternatively, inputting directly an existing tree list for growth projection. Results are displayed on the monitor in terms of stand level characteristics followed by various volumes per acre by one inch diameter at breast height (dbh) classes. If a parallel printer is attached to the computer system, all output on the screen can be printed. Also, screen output can be directed to a disk file in American Standard Code for Information Interchange (ASCII) format which can be imported into most word processors or spreadsheets. Options are available for initializing a new or an existing plantation, grow a stand, perform midrotation thinning, hardwood control and fertilization, and set values for various volume specifications.

TRULOB files

The TRULOB diskette contains three files:

TRULOB.EXE (the executable file)
LOBLOLLY.DAT (an example tree list file for projection)
TRULOB.ICO (an icon that can be used to represent TRULOB in the Windows environment).

Running TRULOB

To run TRULOB, go to the drive and directory in which TRULOB is located and type TRULOB at the DOS prompt. Alternatively, the TRULOB executable can be added as an item to a group window in the Windows environment. The TRULOB.ICO file can be selected instead of the default icons available with Windows.

The TRULOB software is executed by responding to requests for information. When numerical values are displayed, pressing <enter> keeps the existing value. The backspace key can be used to delete a typing mistake.

INITIALIZING A PLANTATION

This section describes the options available for initializing a plantation. Bare ground conditions can be initialized with TRULOB or existing stands can be initialized for subsequent projection.

Bareground

To initialize a plantation from bare ground, it is only necessary to specify the site index, number of trees planted, the percent surviving at age 1 and whether it was planted on a poorly drained and no bedded site or not. Once this information has been inputted to TRULOB, the stand will be advanced to age 8 where a tree list will be generated from the Weibull distribution based on the stand attributes at age 8.

Existing stand - no tree list

To initialize an existing plantation, the user must enter the current age, site index and number of trees surviving. If the age is less than 8, the user must also specify if the stand exists on a poorly drained and not bedded site. If the stand is older than 7 years, an optional input is the existing basal area. TRULOB will then generate a tree list using the Weibull distribution and the stand information.

Existing stand - tree list

An existing tree list can be inputted directly into TRULOB. Inputting a tree list requires a header record with stand-level information followed by the individual tree records with dbh, total height and crown class information. An existing tree list stand must be at least 8 years old. The variables and proper formats are

Variable	Column and Format	
For record type = 1 (header card)		
Record type = 1	1	X
Plot identifier (character variable)	2-6	XXXXX
Plot size (acres)	7-11	XX.XX
Plot age (years)	13-14	XX
Age of fertilization (years)	16-17	XX
Pounds per acre of nitrogen applied	19-21	XXX
Phosphorus indicator variable (1 = P applied, 0 = no P applied)	23	X
Age of thinning (years)	25-26	XX
Basal area after thinning (sq. ft/ac)	27-31	XXX.X
Basal area before thinning (sq. ft/ac)	32-36	XXX.X
Hardwood basal area indicator (1 if hardwood basal area is specified, 0 if hardwood basal area is not specified)	38	X
Percent of total basal area in hardwoods	39-42	XX.X
For record type = 2 (tree card)		
Record type = 2	1	X
Tree identifier (character variable)	2-6	XXXXX
Dbh (in.)	8-11	XX.X
Total height (ft.)	13-16	XX.X
Crown class	17	X

An example tree list file called <loblolly.dat> is supplied with the distribution diskette. It defines a hypothetical stand with an identifier of 00001 where the plot size is 0.10 acres, age is 15, age of fertilization is 11 when P and 200 lbs N were applied; it was also thinned at age 11 from 130 sq. ft. of basal area to 85 sq. ft.; percent of total basal area in hardwoods is specified at 15.0 percent.

Hardwood competition

Hardwood competition effects on loblolly pine growth are accounted for in TRULOB in two ways. If hardwood competition is not explicitly specified, then growth projections are made using equations that do not include the hardwood component as a model driver. Thus, growth and yield predictions will reflect the average level of hardwood competition found in the regionwide thinning study data which is about 5 percent of the total overstory basal area.

If the amount of overstory basal area as a percent of the total basal area is known, then it can be specified as an explicit input to TRULOB. Growth projections and predictions are then made using equations that include the hardwood component as a model driver. Levels from 0 to 90 percent of the total basal area in hardwoods can be specified.

PROJECTING A PLANTATION

Once initialized, a plantation can be projected to specific values of one of seven stand target criterion: age (1), basal area (2), quadratic mean dbh (3), dominant stand height (4), merchantable cord volume (5), average crown ratio (6), or relative spacing (7). Once the target criterion and value have been selected, TRULOB projects the stand to the age that meets or just exceeds the target value. This allows projection based on stand development parameters rather than on age which can be useful for scheduling midrotation silvicultural treatments. TRULOB will allow projection to any age up to 100, but after age 25 the only projection criterion that can be used is age.

MIDROTATION SILVICULTURAL TREATMENTS

This section describes how to use TRULOB to simulate midrotation thinning, fertilization and hardwood control.

Thinning

TRULOB supports three thinning treatments: row, low and combination row and low. The row thinning option allows the user to specify a row removal interval between 2 and 6, inclusive. Then, the thinning algorithm removes a constant proportion of trees from each dbh class. For example, a row removal rate of 1 in 5 means that 20 percent of the trees are removed in a constant proportion across all diameter classes.

The low thinning option offers two cutting limits. The diameter limit prompts the user to select a minimum and maximum dbh for cutting. That is, all trees will be removed between these two limits. The basal area limit allows the user to specify both a minimum dbh below which no trees would be removed and a residual basal area that is left after the thinning.

The row and low option combines the two previous options and allows both thinnings to be applied in one operation.

Altering hardwood basal area

The percent of the total stand basal area that can be attributed to hardwoods can be altered at any point in the rotation. Values from 0 to 90 percent can be specified. Reducing the percentage could be used to simulate the effects of midrotation hardwood control on plantation development.

Fertilization

Midrotation fertilization can be simulated using TRULOB by specifying levels of phosphorus and nitrogen. Phosphorus fertilization is treated as a “switch”; either phosphorus is applied or not. Nitrogen fertilization rates from 50 to 400 pounds per acre can be specified. When the fertilization option is invoked, modified dominant height and diameter growth equations are used to make appropriate growth projections. When phosphorus is applied, adjusted dominant height growth is used to recalculate site index.

OUTPUT OPTIONS

This section describes various output options available in TRULOB.

ASCII Data File

When the ASCII data file option is activated by the user, TRULOB saves the stand-level and diameter distribution output at each projection age during the run into a data file named by the user. At each age, a stand-level header card is written first followed by the diameter class information according to the following format:

Variable	Column and Format	
----------Header Card ------------		
Age	2-4	XXX
Site index (ft)	5-10	XXXX.X
Dominant height (ft)	11-16	XXXX.X
Average height (ft)	17-22	XXXX.X
Loblolly basal area (sq.ft/ac)	23-28	XXXX.X
Trees surviving per acre	29-34	XXXX.X
Relative spacing	35-39	XX.XX
Merchantable cord volume per acre	40-45	XXXX.X
Average crown ratio	46-51	XXX.XX
------------ Tree Card -------------		
Diameter class (in.)	1-8	XXXXXXXX
Number of trees per acre	9-20	XXXXXXXXXX.X
Average height (ft.)	21-31	XXXXXXXXX.X
Basal area (sq.ft/ac)	32-42	XXXXXXXXX.X
First volume	43-53	XXXXXXXXX.X
Second volume	54-64	XXXXXXXXX.X
Third volume	65-75	XXXXXXXXX.X

Once a data file has been created, it can be easily ported to spreadsheet programs, word processors and other analysis packages for further evaluation.

Volume unit specification

The TRULOB stand table output displays three columns of volumes. The volumes displayed in the three columns depend on the volume output option selected by the user. The first available option is to express volumes in cubic feet. When this option is chosen the first volume output column presents total outside bark cubic feet for all diameter classes. The second volume column presents merchantable cubic foot volumes for the 5-inch class and above to a 4-inch top diameter outside bark. The third column presents a user-specified merchantable volume either inside or outside bark to any selected diameter class and top diameter outside bark limit.

The second volume option available in TRULOB is the cords/board feet option. In this option the first volume displayed is total outside bark in cubic feet (just as volume output option one, above). The second column presents cord volumes outside bark for the 5-inch class and above to a 4-inch outside bark top (again, just as volume output option one, above). The third column presents International 1/4, Doyle or Scribner board-foot volumes to a selected diameter class limit.

The third volume option allows the user to specify three volume equations of the form: $a + bD^2H$ where a and b are coefficient values inputted by the user. This option is useful for users who wish to apply custom volume or weight prediction equations.